

Music and Engineering: Effects

Timothy Hoerning

Fall 2017
(Last modified 2017-10-31)

What are effects?

- Musical Effects are signal processing devices (or algorithms) that take one sound and alter it in some way.
- The Waveshaper synthesis block can be thought of as an effect.
- Traditionally implemented as analog or electromechanical devices.
 - Often built into amplifiers (tremolo, reverb) – tube or transistor
 - Offered as standalone devices later.
- Now implemented in analog and digital
 - Mass produced vs. boutique
 - Multi-purpose & Multi-effect

Types of Effects

- Amplitude Based
 - Varies the gain/volume of the effect across all frequencies
- Filter Based
 - Varies the gain/phase response of the signal with different amount on each frequency
- Time Based
 - Uses time delays to simulate digital-type filters

Background Topics

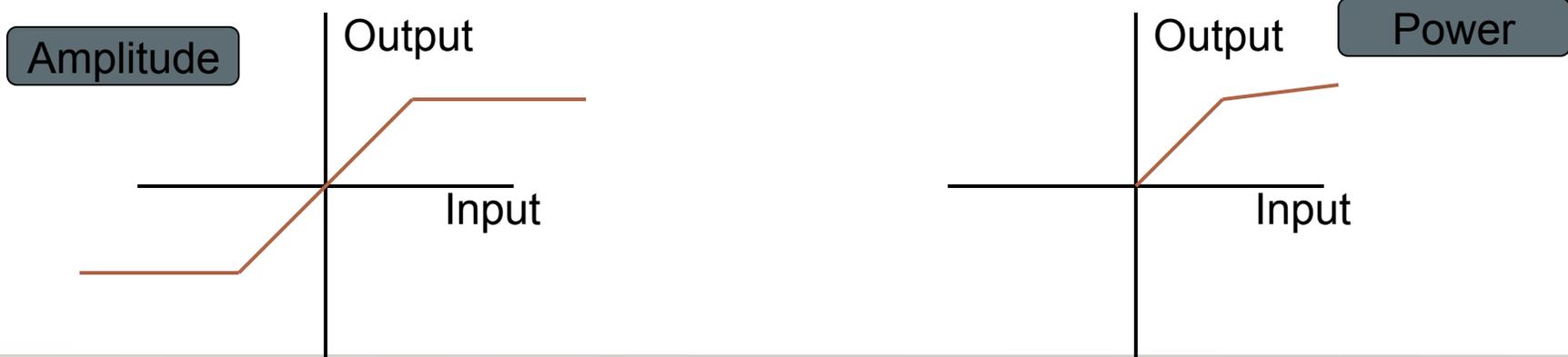
- Time Response and Time Delay
- Frequency Response
 - Bode plots / Mag Phase Plots
 - Digital / Analog Domain
- Spectrogram – Time and Freq together
- Distortion
 - Total Harmonic Distortion
 - Inter-Mod Distortion
 - Phase Distortion
- Physical/Electrical construction

Time / Freq Response

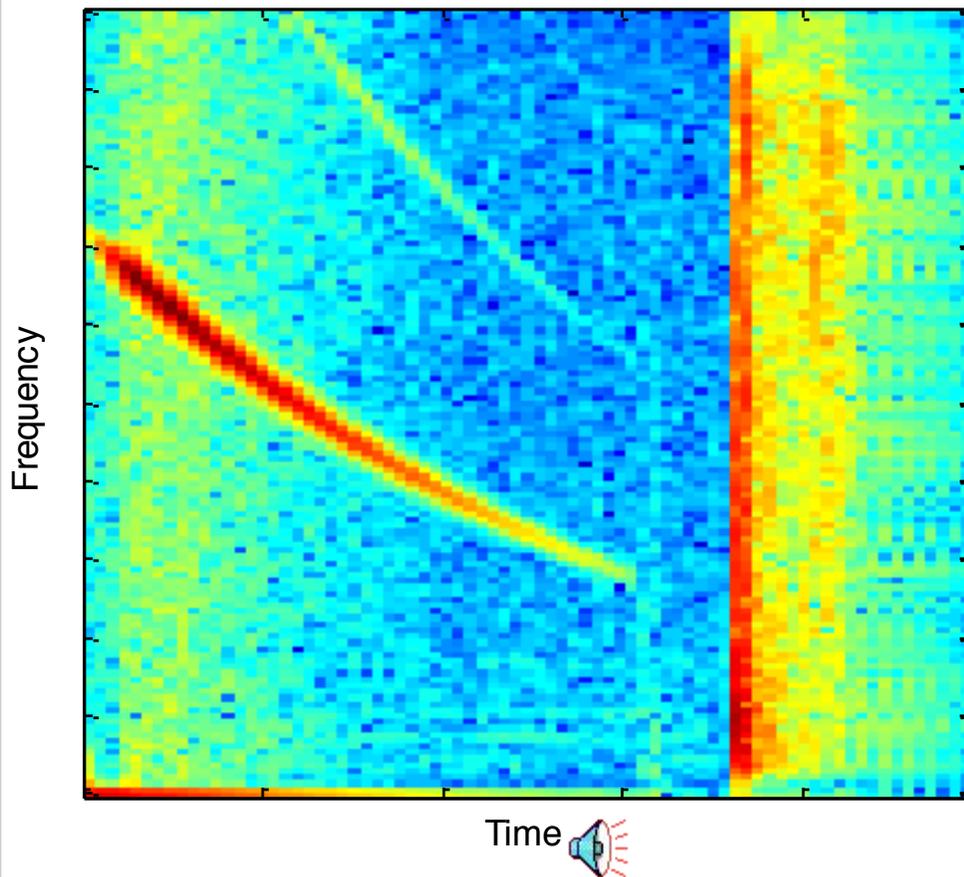
- Nothing special about this with respect to common engineering uses
- Frequency Domain should almost always be log scale frequency and deciBels in magnitude

Graphical Transfer function

- Can be expressed in amplitude or power
- Input is expressed along the X-axis, “reflected” by the transfer curve and read out along the Y-axis



Spectrogram



- MATLAB's xpsound demo allows the user to explore the time domain, freq domain and both at once spectrogram
- The signal shown to the left is the dropping egg.
 - The curve in the left hand section represents the falling pitch as the egg drops
 - The line about 2/3 of the way through is the "splat" impulse. Notice the broadband nature of the impulse

Distortion

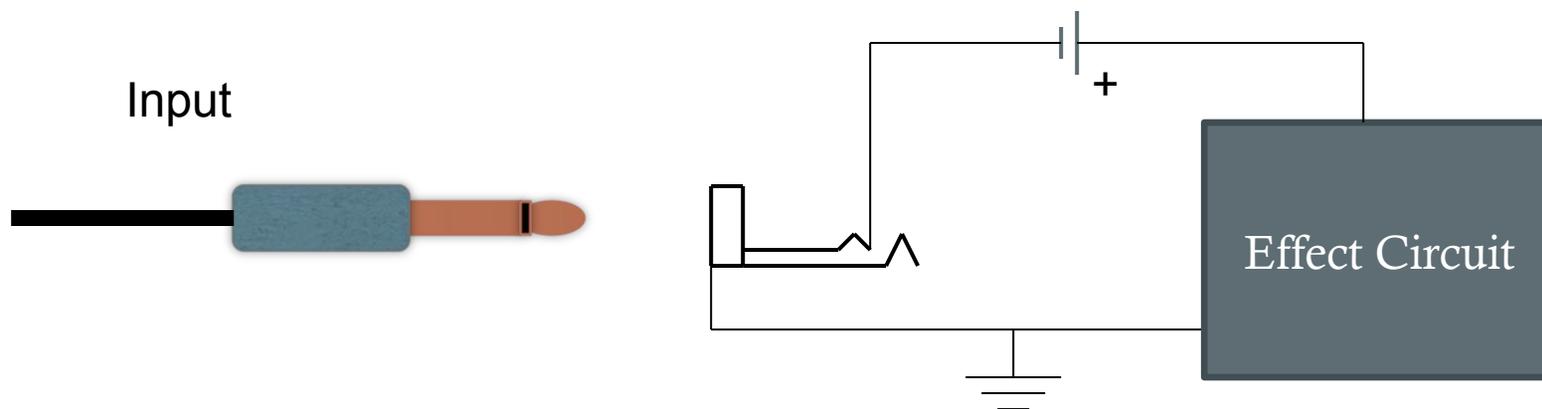
- Total Harmonic Distortion – Distortion of a single tone through a non-linearity. Adds harmonics (even harmonics are octaves, odd harmonics are other notes)

$$THD = \frac{\text{power in overtones}}{\text{fundamental power}}$$

- Intermodulation Distortion – Occurs when two or more tones are summed before a non-linearity. Creates frequencies at sums and differences of the fundamentals and overtones (f_1+f_2 , f_1-f_2 , $2f_1-f_2$)
- Non-linearities can leave the amplitude intact but delay the phase in a non-linear fashion

Powering

- Most pedals use 9 volts (from the battery)
 - Other variations exist (18 volts, AC power)
 - Many solutions exist for powering pedals without batteries
- Power tied to input jack
 - Tip/Ring/Shield connector used – Tip is hot signal, ring is connected to battery negative terminal and shield is connected to ground. Inserting a mono 1/4" plug connects the ground circuit and turns on the pedal.



Construction Issues

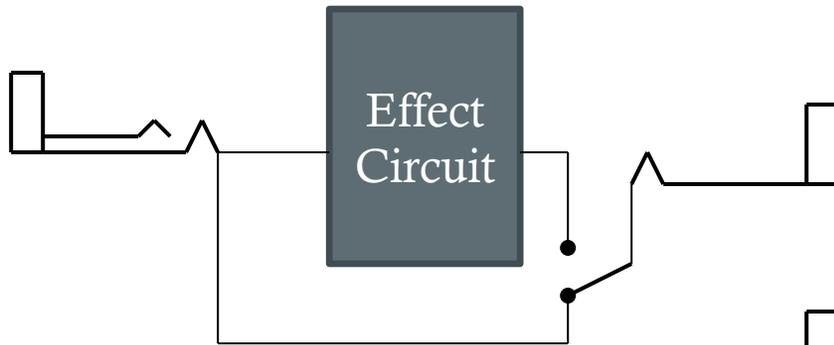
- Input / output impedances
 - Care should be taken to not load the guitar with a low input impedance (this relates to the type of bypass/buffering used)
- Board quality
 - Perf board (soldered or point to point wire wrap)
 - Printed circuit board
 - Some DIYs have even been known to use cardboard.

Bypass

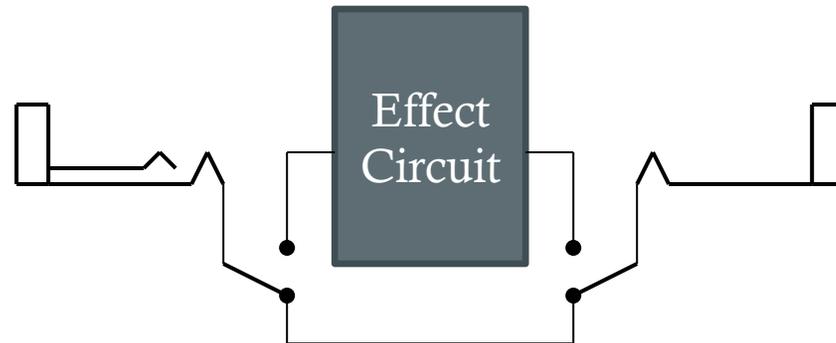
- Bypass is the state of the pedal when it is not affecting the input signal
- Bypasses typically fall in one of several varieties
 - Solid State
 - Commonly found in most mass produced pedals. Signal is routed through a buffer stage when the effect is not engaged.
 - Most common on Boss, DOD and Ibanez
 - Single Ended Bypass
 - Only the output of the effect is switched. The input jack is hardwired to the input of the effect. This is a substantial issue when the effect has low input impedance.
 - The original effects from the 60s and 70s used this almost exclusively
 - Wah Pedal
 - Fuzz Face
 - “True” Bypass
 - Typically uses a DPDT or 3PDT (w/ LED) to mechanically connect or disconnect the input and output jacks from the effect circuit.
 - Can be a problem if multiple TB effects are used without a decent buffer feeding them.

Bypass Examples

Single Ended



True-Bypass



Others:

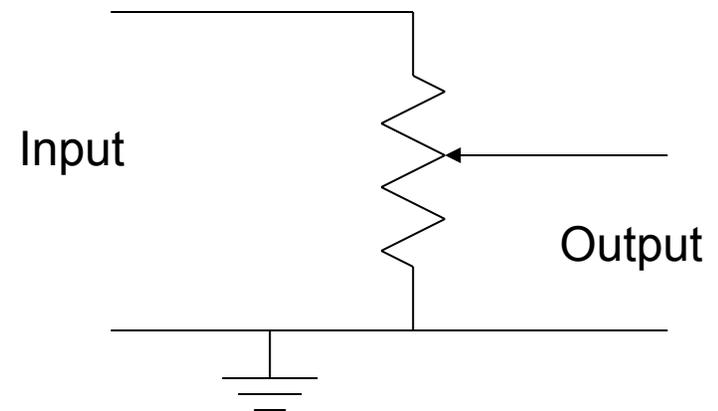
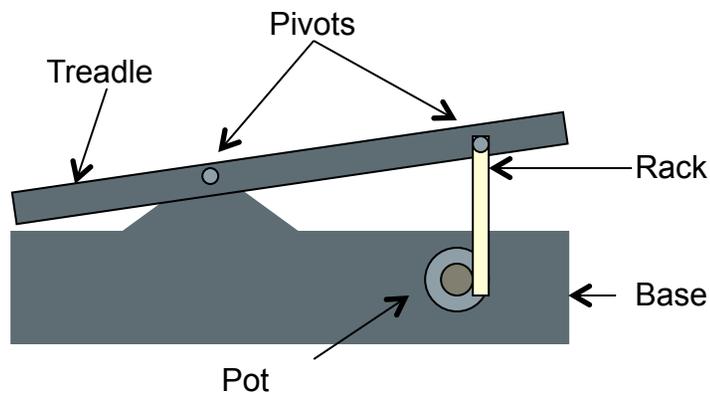
- Millenium Bypass (
http://www.geofex.com/article_folders/millenum/millen.htm)

Amplitude Based

- Volume Pedal
- Boost / Pre-Amp
- Tremolo
- Ring Modulator
- Compression/Limiter
- Expansion/Noise Gating
- Distortion
 - Overdrive/Saturation
 - Distortion
 - Fuzz

Volume Pedal

- Same circuit as the volume control in a guitar.
- Simple Voltage divider
- Wiper of potentiometer (pot) has a “pinion” gear on it instead of a knob. A rocker foot pedal (treadle) has a “rack” suspended below it which engages the gear and turns the pot. Other variants use opto-isolators instead of the pot.



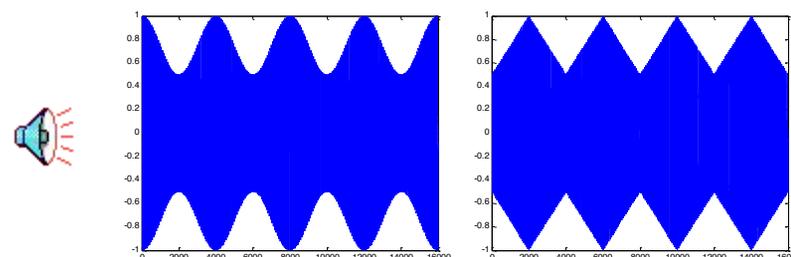
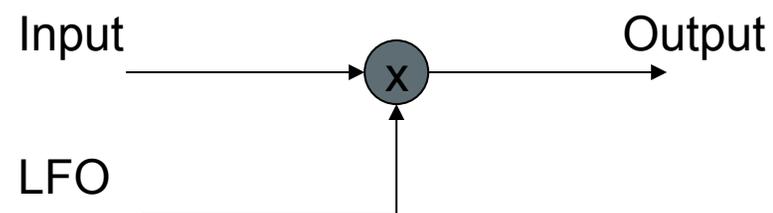
Musical Example:

- When the Children Cry – White Lion
- Xanadu - Rush



Tremolo

- Multiply the input signal by the output of a Low Frequency Oscillator (LFO).
- LFO can vary in shape (sine, square, etc.), frequency, amplitude (typically referred to as depth)
- Can also use different phase LFOs to get a stereo effect.
- Graphs at right show Tremolo with sin and triangle wave modulation. Depth is set to about 50% and the modulating signal is at 2Hz.



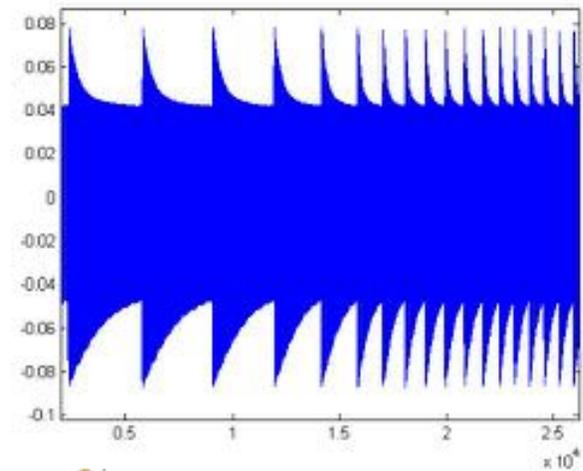
Musical Examples:

- Boulevard of Broken Dreams – Green Day
- Do Right - Tommy Conwell
- The Refugee – U2



Percussive Tremolo

- One of the lesser used variants of Tremolo is Percussive Tremolo
 - Usually created by a unijunction transistor
 - Not currently being produced
 - Modulating wave shape looks like a trail of decreasing exponentials



Musical Examples:

- *Some songs* – Spaceman 3

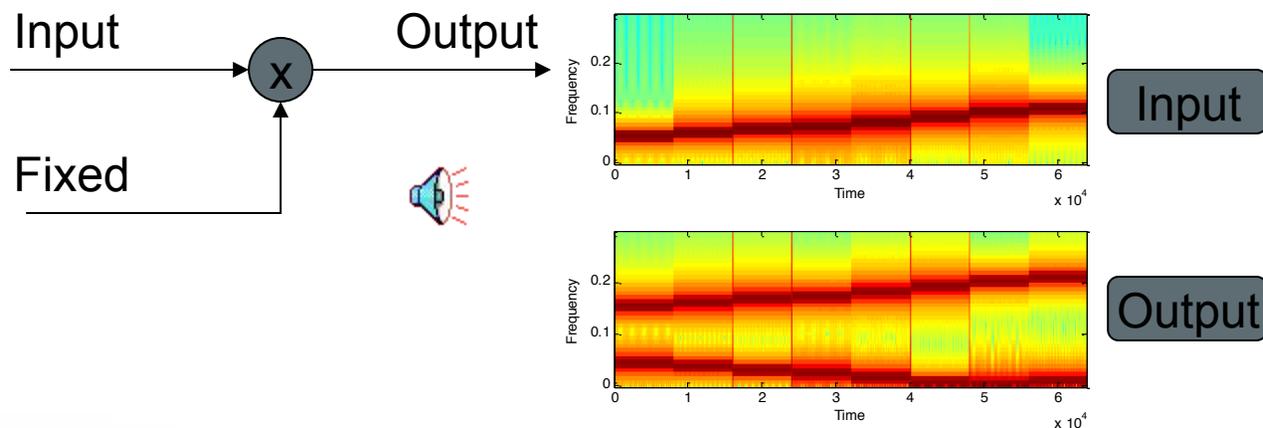
Boost / Pre amp

- Designed to be an extra bit of “clean” gain to add extra “oomph” to a signal before an amplifier
- Also good for buffering the guitar signal so as not to load it from other effects with low input impedances (Fuzz-Face, Crybaby Wah). Sometimes built into guitars (active pickups) or connected to guitars (LPB-1)
- Often used to drive the input stage of a tube amp into saturation. No distortion from the pedal, but the tube-amp is driven into saturation.
- Canonical Pre-amp is a “wire with gain” – no coloring in the frequency domain
- Can be build using tubes, transistors or Op-Amps. A simple inverting or non-inverting amplifier circuit can serve as a pre-amp



Ring Modulator

- Same notional schematic as the Tremolo. Instead of LFO with variable depth, use audio freq with full amplitude.
- Output includes the sum and difference frequencies.
- Very non-musical effects. Sum and difference frequencies are not musically related to input.
- Spectrogram below shows a sine-wave major scale starting at A=220Hz and the output when mixed with a 400Hz fixed frequency.



Musical Examples:

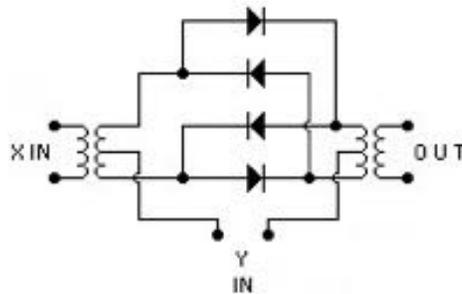
- Tapeworm – Pigface
- Jellyfish Blues – Buffalo Daughter
- Paranoid – Black Sabbath (right channel only)

Ring Mod continued

- Explanation of sum and difference comes from the simple trig identity.

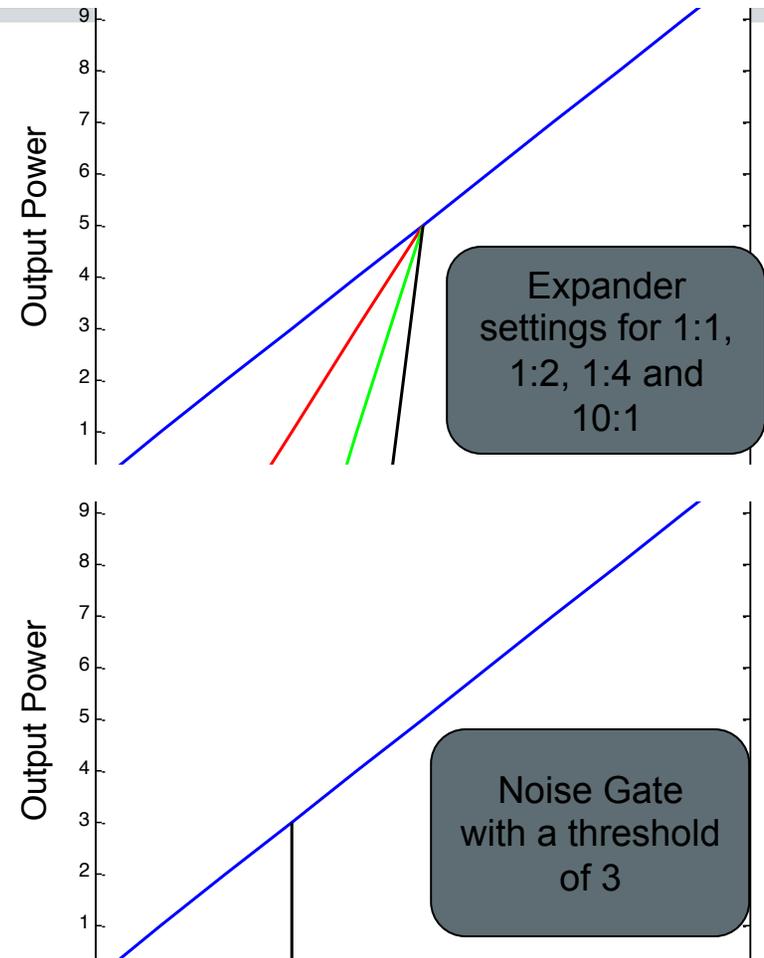
$$\cos(a) \cos(b) = \frac{1}{2} (\cos(a + b) + \cos(a - b))$$

- The following passive circuit can be used to Generate a ring modulated signal
 - It is often used in RF as a mixer for up or down conversion.
 - The ring of diodes makes it act like an inverter when the control signal is the second input.
 - See References for a better explanation of how this works as a RF mixer



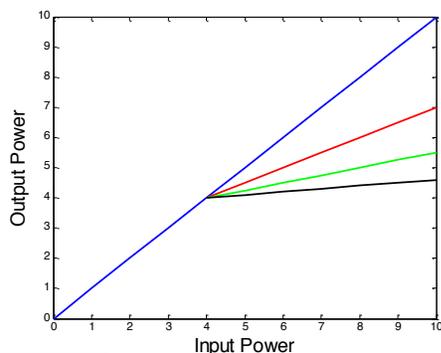
Graphical Transfer Function

- The curves at right show a graphical representation of the expander and noise gate curves
- The expander curve shows how the amplitude is lower for low power signals and increases to a maximum of 1 for higher power signals
- The noise gate carries this to the extreme by making the gain $-\infty$ for the signals below the threshold

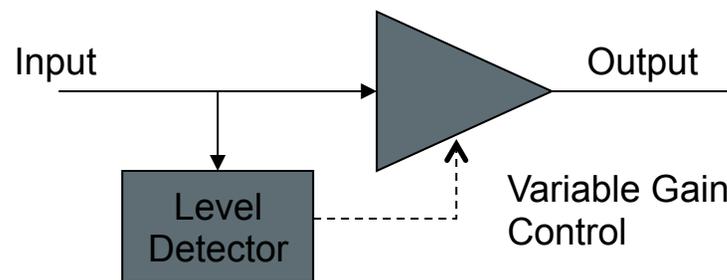


Limiters / Compressor

- Controls the gain of the circuit based on short-term power estimates of the input signal
- “Compresses” signals that exceed the determined threshold. Reduces the gain for these components

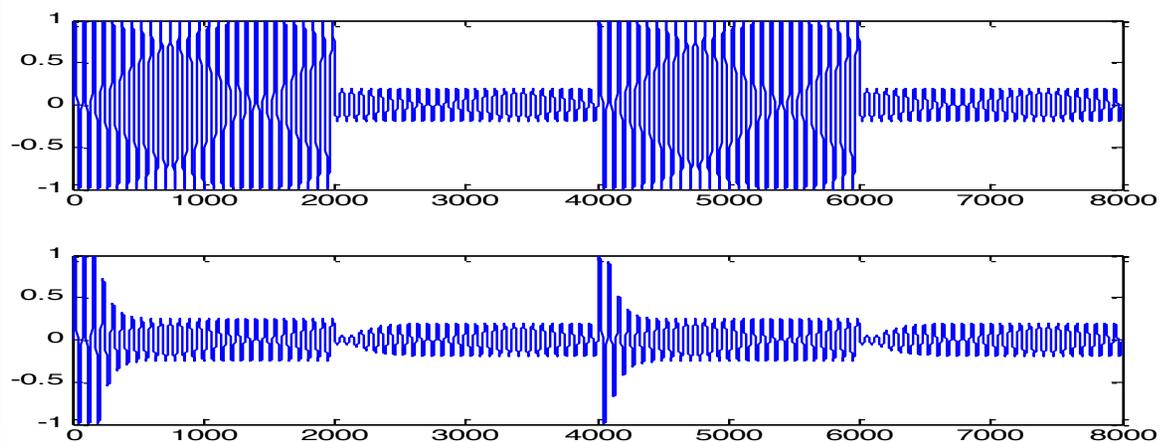


Compressor settings for 1:1, 2:1, 4:1 and 10:1



Attack / Release

- Attack and release time control how quickly the level detector / gain adjustment circuit responds to transients in the input signal. Over- and undershoot result.
- Digital processing can alter gain quicker than analog, but there is always the delay for the averaging window
- The curve below shows the output of a Tremolo effect put through a 4:1 compressor. Notice the reduction in dynamic range as well as the attack/release times when the signal is louder/quieter than it ideally would be



Original



Compressed

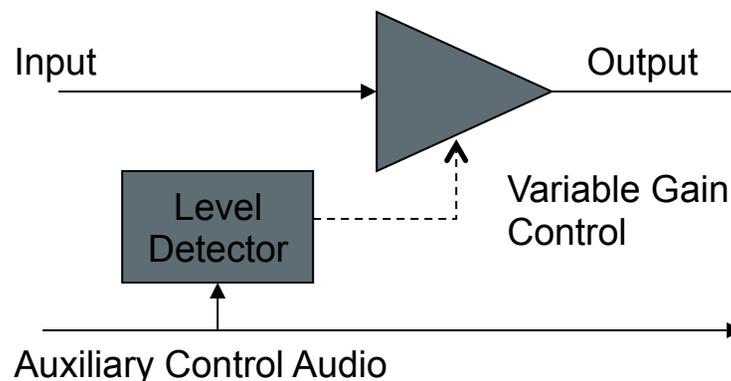


Musical Examples:

- Kiss – Prince
- Soft & Wet – Prince
- Under the Bridge – Red Hot Chili Peppers

Sustain / Ducking

- By increasing the gain after a compressor, the average level is kept at high level. This acts as a clean sustain.
- By using a different signal for control and process, you get a “ducking” processor. This is typically used to mute background music when an announcement is made (on a store PA or on the radio)



Expansion / Noise Gating

- The compressor compresses the dynamic range. i.e., it reduces the gain above a threshold
- The expander expands the dynamic range by reducing the gain BELOW a threshold.
- Carried to the extreme, the noise gate reduces the gain to zero below a threshold. This shuts off the output for signals that are effectively noise. Problems can arise when decaying signals fall below the threshold.

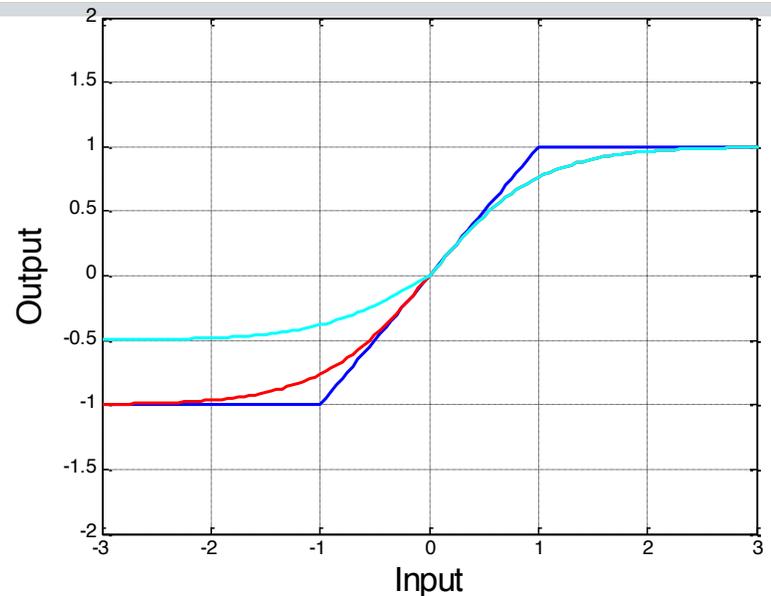
The Distortion Spectrum



- Signal can vary from clean ($\sim 0\%$ THD) to all out fuzz (100% THD – square wave)
- “Touch-sensitive” describes a device (typically tube amplifier or tube emulator) which can vary between clean and overdrive (or overdrive and distortion) based on the physical attack on the strings at the guitar.
- Remember from circuits, half wave symmetric signals contain only odd harmonics. Even harmonics sound “better” (because they are octaves).

Hard Clipping vs. Soft Clipping

- Soft clipping rounds the edges of the signal. There are no sharp discontinuities.
- Hard clipping simply clips anything beyond a threshold. This creates a discontinuity and adds higher order harmonics.
- The third case is an asymmetric soft-clipping. This introduces both even and odd harmonics (the symmetric clipping only created odd-harmonics).



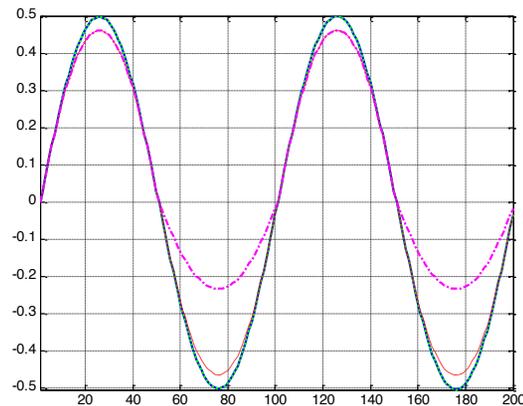
Musical Examples:

- *Any Metal Tunes – Any Metal Artist.*

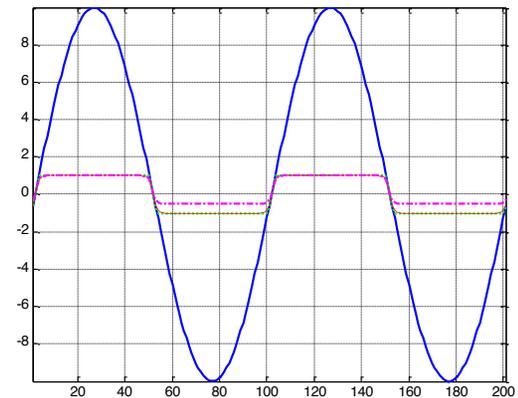
Test Vector

- Create a sine wave that varies in amplitude from 0.5 to 10 over a span of about 20 seconds
- Set a hard threshold of 1 and the soft symbol to have its maximum excursion at 1

Outputs at beginning

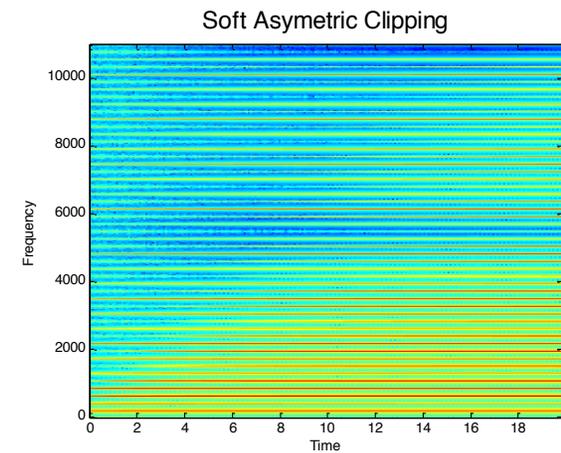
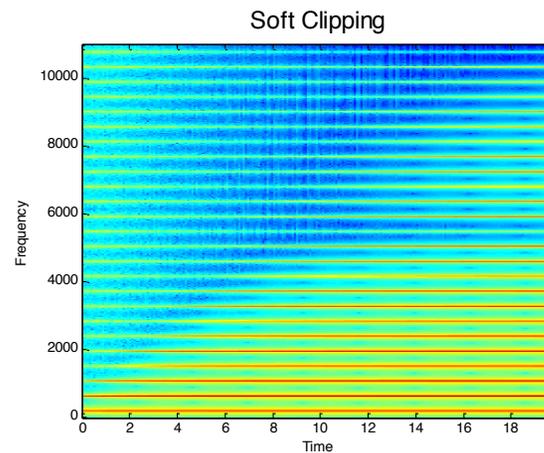
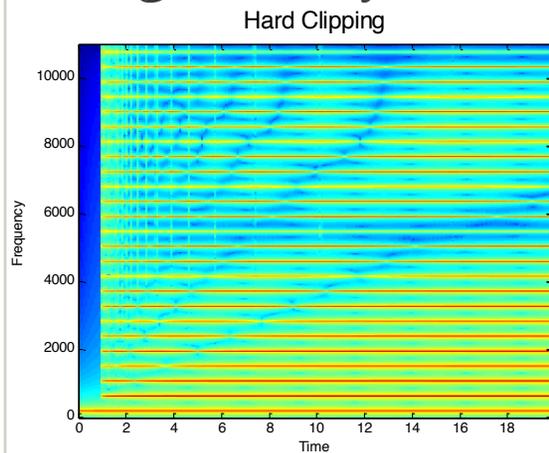


Outputs at end

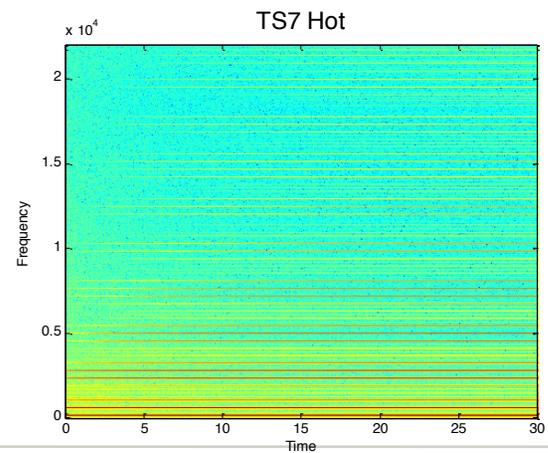
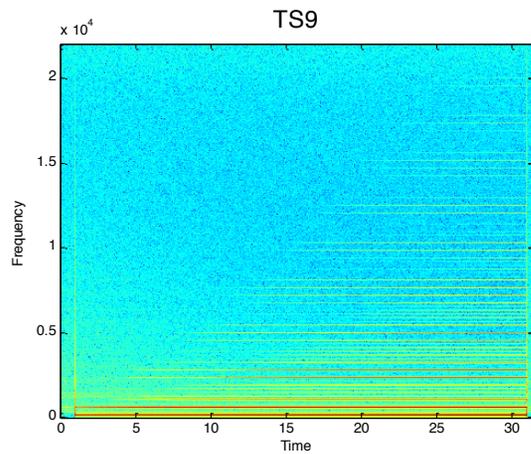
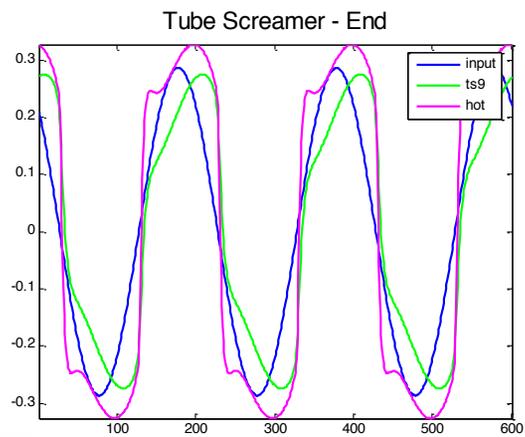
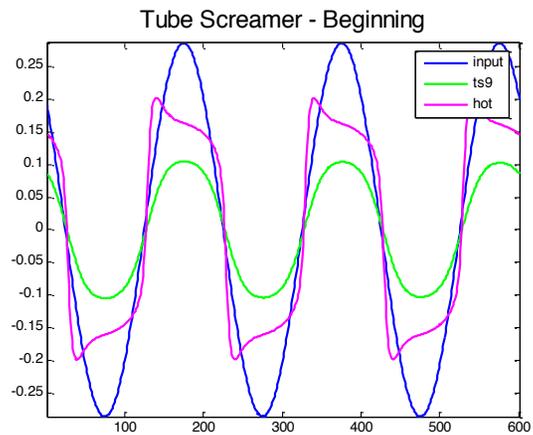


Hard Clipping vs. Soft Clipping

- Soft clipping adds harmonics “gradually” depending on the amount of distortion
- Hard clipping adds harmonics as soon the threshold is exceeded
- Asymmetric clipping adds even and odd harmonics gradually



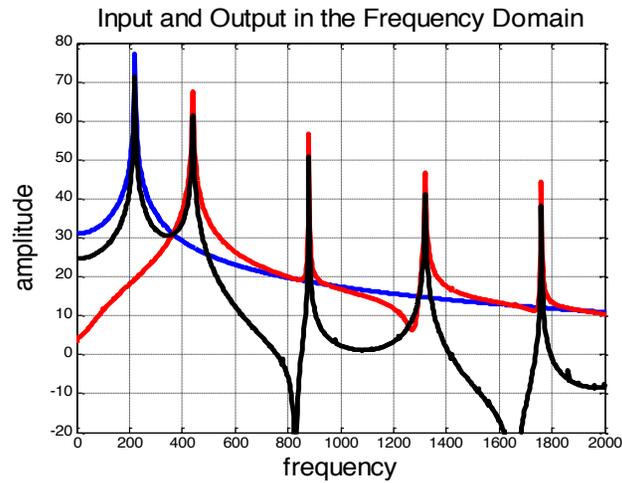
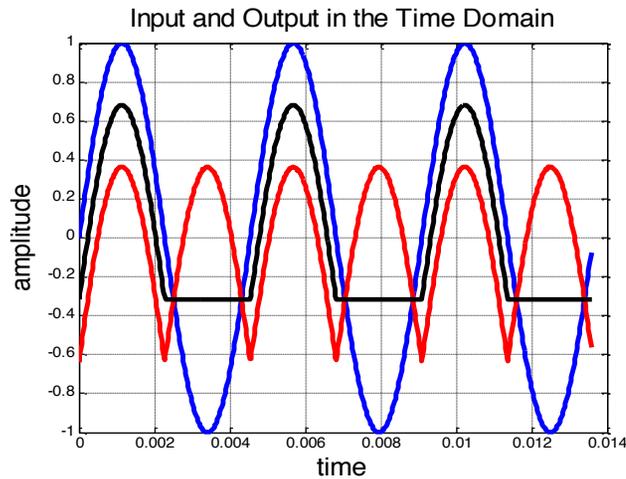
Tube Screamer



Octave Generators

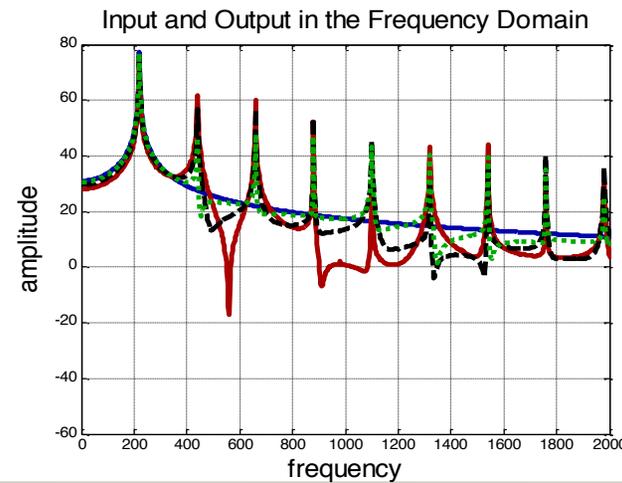
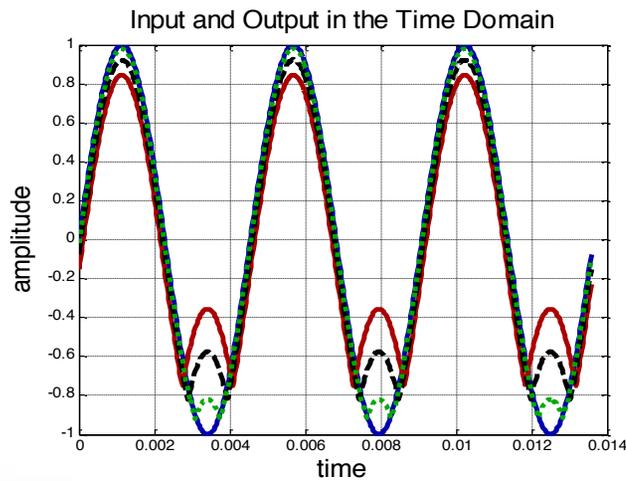
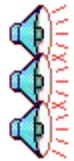
- Octave Up
 - Generated through rectification
 - Full Wave rectification gives only octave up
 - Half Wave rectification gives octave up plus fundamental
 - Can vary by partial rectification. (see next slide for example)
 - Two signals can give a ring mod like effect.
- Octave Down
 - Generated with a flip flop
 - The input audio signal becomes the clock for the flip flop
 - The circuit gets confused when two input notes are present and doesn't "track" properly
 - Heavy distortion leaves the square flip flop w/ minimum amplitude reconstruction.
 - To get a cleaner signal, more of the amplitude envelop can be reconstructed using more elaborate circuits

Rectification



Sound Clips:

- *In*
- *Full Wave*
- *Half Wave*



Sound Clips:

- *In*
- *10% Rect*
- *25% Rect*
- *40% Rect*

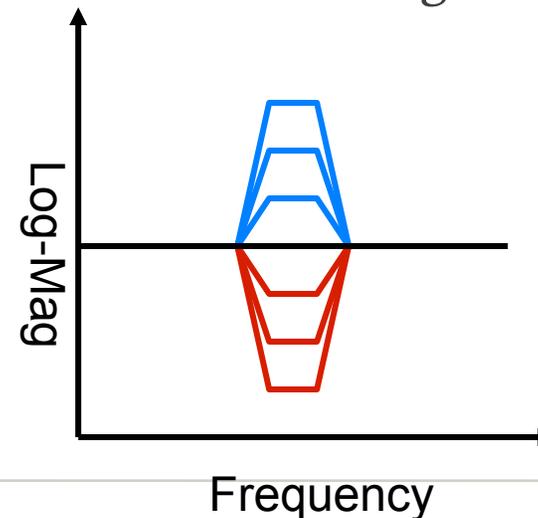
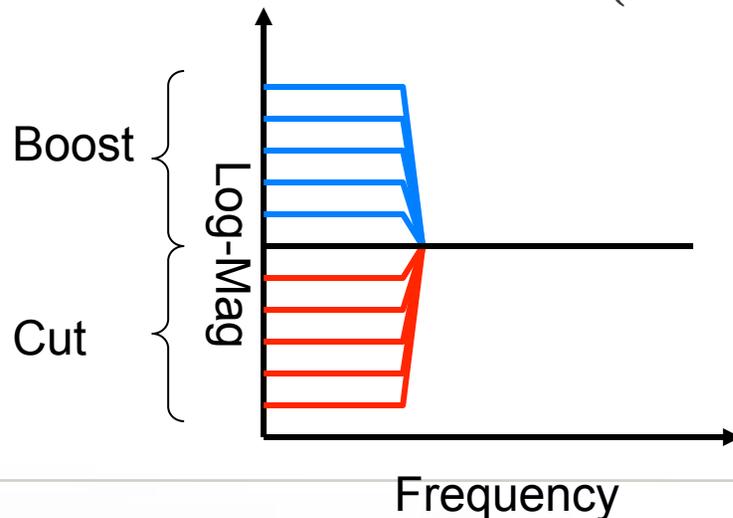


Filter Based

- Equalization
 - Graphic
 - Parametric
- Treble Booster
- Wah Wah / Envelope (Followed) Filter
- Vocoder / Talk Box
- Phase Shifter

Active Filters

- Active Filters by definition require a power supply
- Passive filters can only remove frequency components.
- Active filters can boost as well as cut frequency bands.
 - Also allow for sharper transitions
 - Allow multi-pole filters using solid state devices and capacitors instead of inductors (allows for implementation in integrated circuits)



Basic Parameters

- Break Frequencies (or center frequency) – The frequencies at which the response of the filter changes slope. (i.e. the poles and zeros)
- Bandwidth – The width of the filter in the frequency domain. Usually defined at the point 3dB below the peak signal amplitude.
- Q – The ratio of the center frequency to the bandwidth. Q is generally fairly low for audio applications
- Boost/Cut Amplitude – Amount of amplification or attenuation obtained by a filter. Typically specified in dB with a range of +/- 10dB to +/- 20dB

Some Basic Filtering Effects

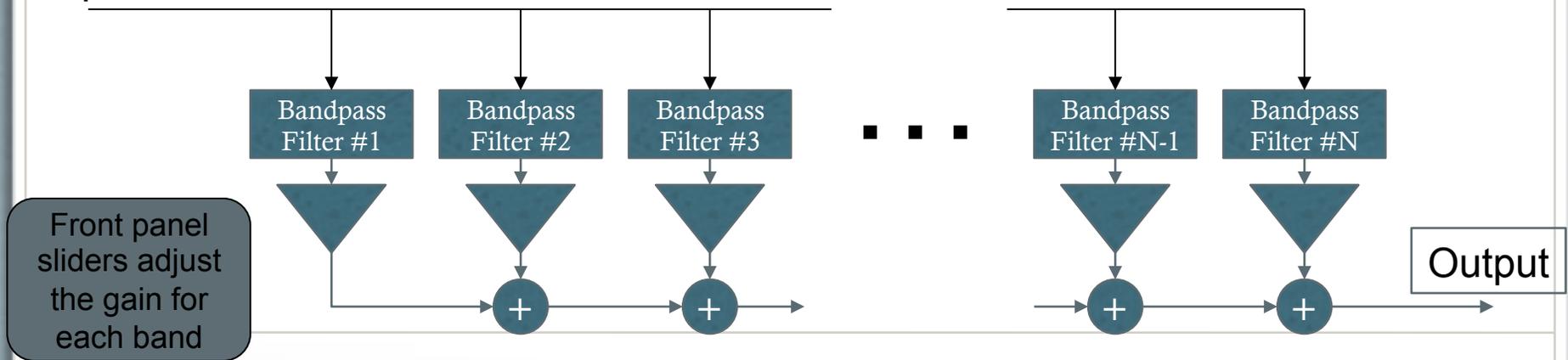
- Treble booster – Preamp combined with a passive high-pass shelving filter
- Mid-range boost control (like on a Powerhouse or Eric Clapton Stratocaster)
- Active electronics on bass guitars – typically high-pass and low pass shelving filters

Equalization

- Named because it was designed to “equalize” the response of the room. The goal was to use the notches and peaks of the equalizer to compensate for resonances and dead spots within a room
- Types
 - Graphic
 - Fixed center frequency, fixed Q, variable amplitude
 - Spaced in octaves (or fraction of octaves, 1/2 octave or 1/3 octave)
 - Parametric
 - Variable center frequency, variable Q, variable amplitude
 - Typically only 3 or 4 bands
 - Semi-Parametric
 - Variable center frequency, fixed Q, variable amplitude



Input

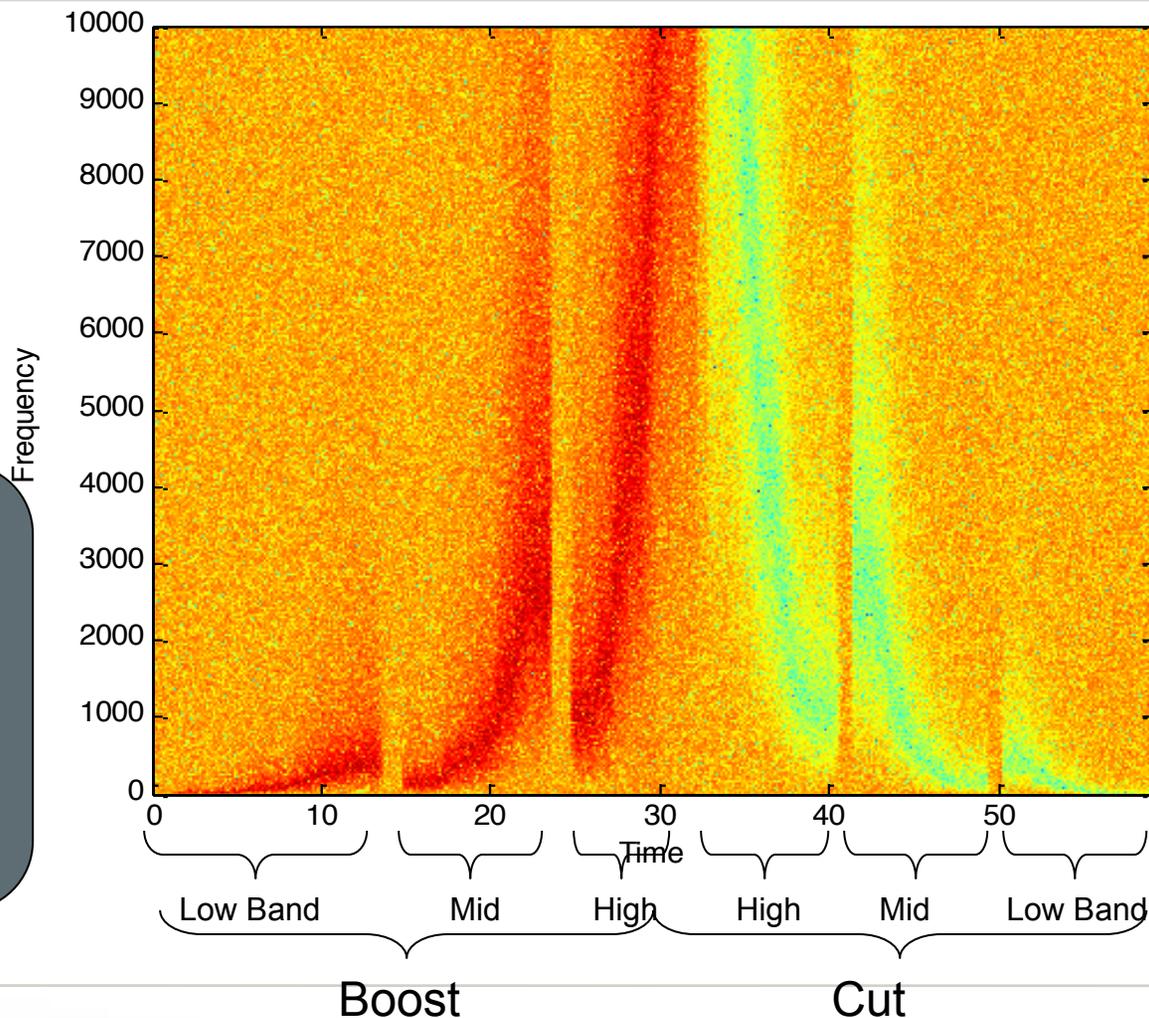


Parametric Equalization Response

Boss Bass Parametric



To create this spectrogram, the bands were swept from low to high first with boost, and then from high to low with cut

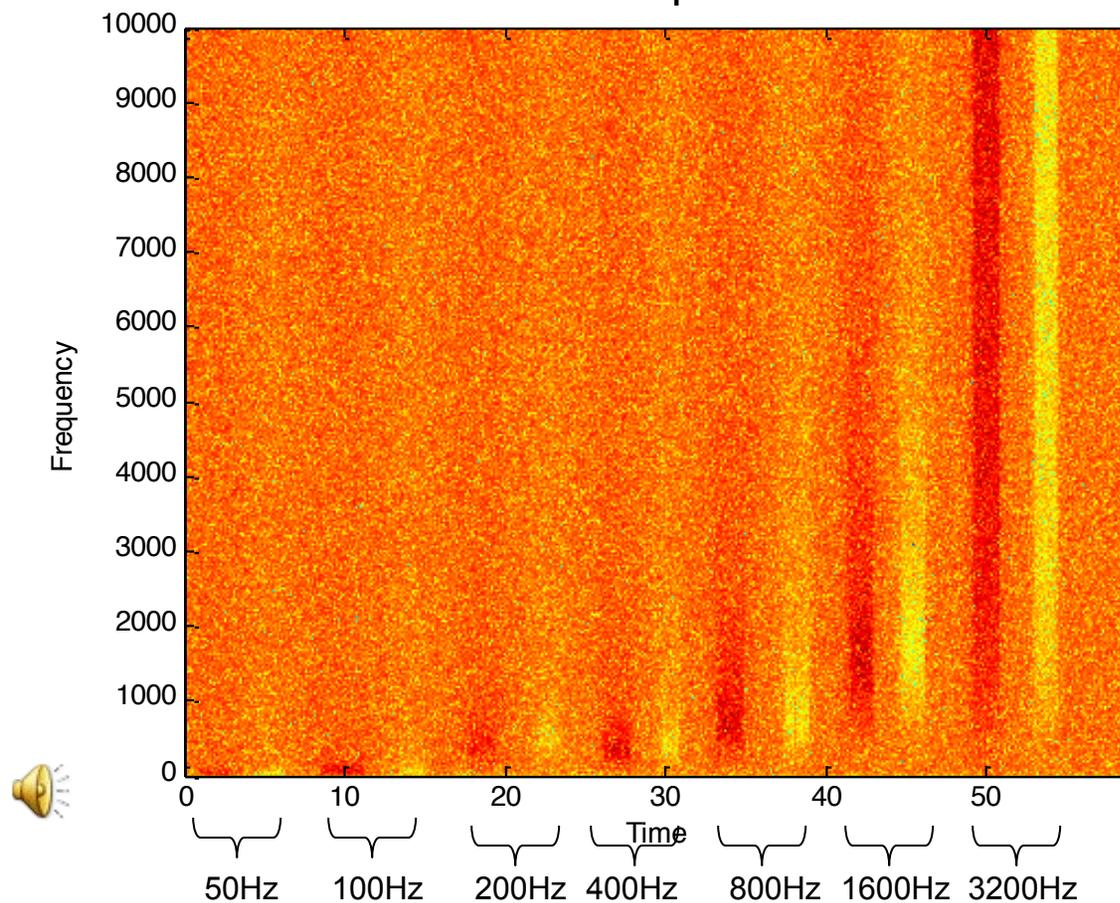


Graphic Equalizer Response



To create this spectrogram, sliders of the Bass Graphic EQ were swept from boost to cut and in frequency from left to right

Bass Graphic EQ

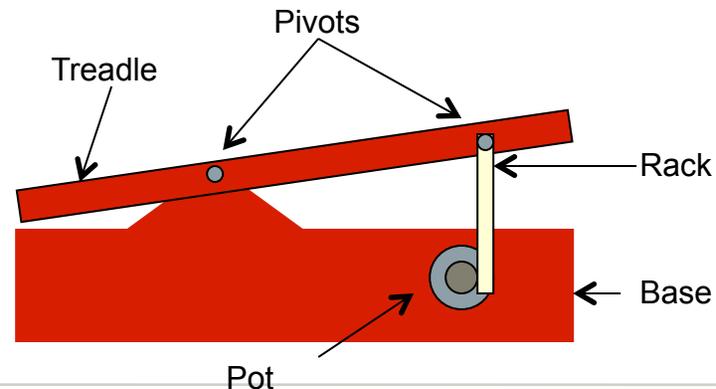


Wah Wah

- A Wah Wah pedal is at the core a band pass filter
- Named for the “wah” sound made by moving the pedal from low frequencies to high.
- Physically constructed similarly to a volume pedal with a treadle, pot and rack. As with volume pedals, physical construction and method of control differ with different manufacturers.
- The center frequency of the filter is controlled via the treadle. Different manufacturers and models differ in the minimum and maximum center frequency and the Q of the filter. Some allow for adjustment of these parameters.

Musical Examples:

- Voodoo Child (Slight Return) – Jimi Hendrix
- Yankee Rose – David Lee Roth
- Still Raining Still Dreaming – Jimi Hendrix
- Sweet Child O’ Mine – Guns & Roses
- (Anesthesia) Pulling Teeth (bass solo) – Metallica
- *Any Song from the Black Album* - Metallica



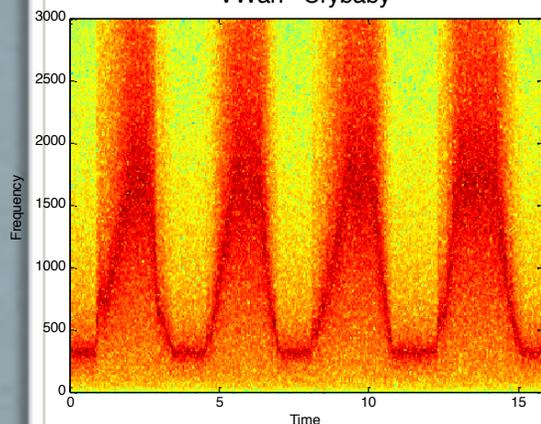
Wah Wah Variables

- Shaping
 - Center Frequency Range
 - Min Frequency
 - Max Frequency
 - Q
 - Non-Linearities
 - Inductors
- Control
 - Potentiometer
 - Oldest Method
 - Prone to getting scratchy
 - Optical
 - Used by Morley
 - Originally light bulb
 - Now LED
 - Capacitive
 - Used by DOD FX-17
 - Hall Effect
 - Used by Boss V-Wah

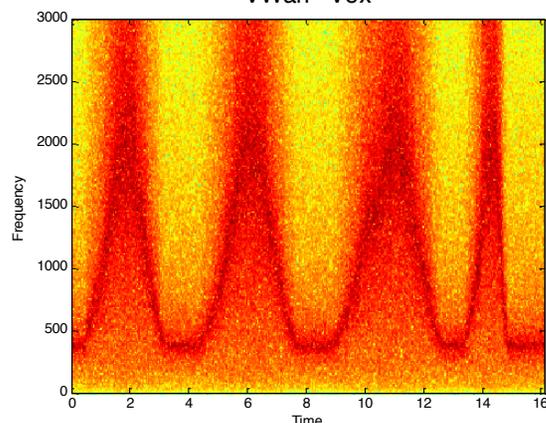


Wah Wah responses

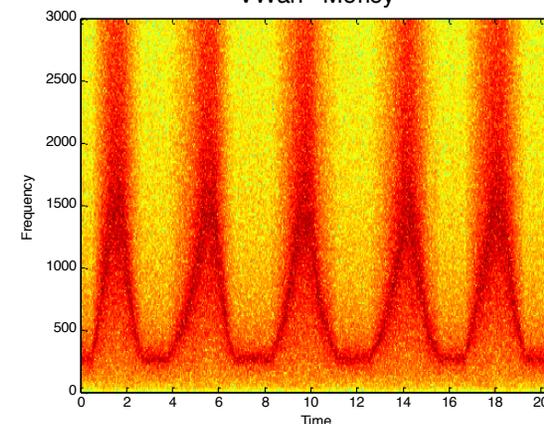
VWah - Crybaby



VWah - Vox



VWah - Morley



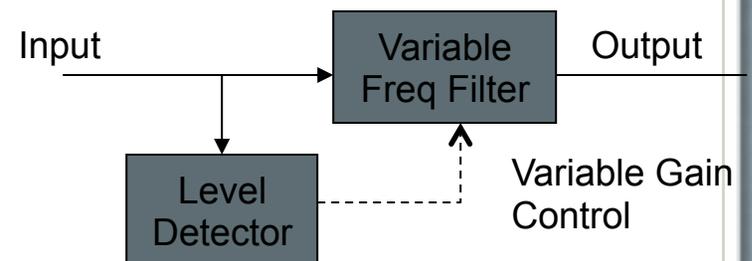
The V-Wah includes several models as well as a range control. The three spectrograms above show the Dunlop Crybaby, Vox Wah, and Morley Wah models with the same range setting. Notice the difference in minimum and maximum frequency. You can also see a difference in Q for some of the wahs at higher frequencies.

Envelope Filter

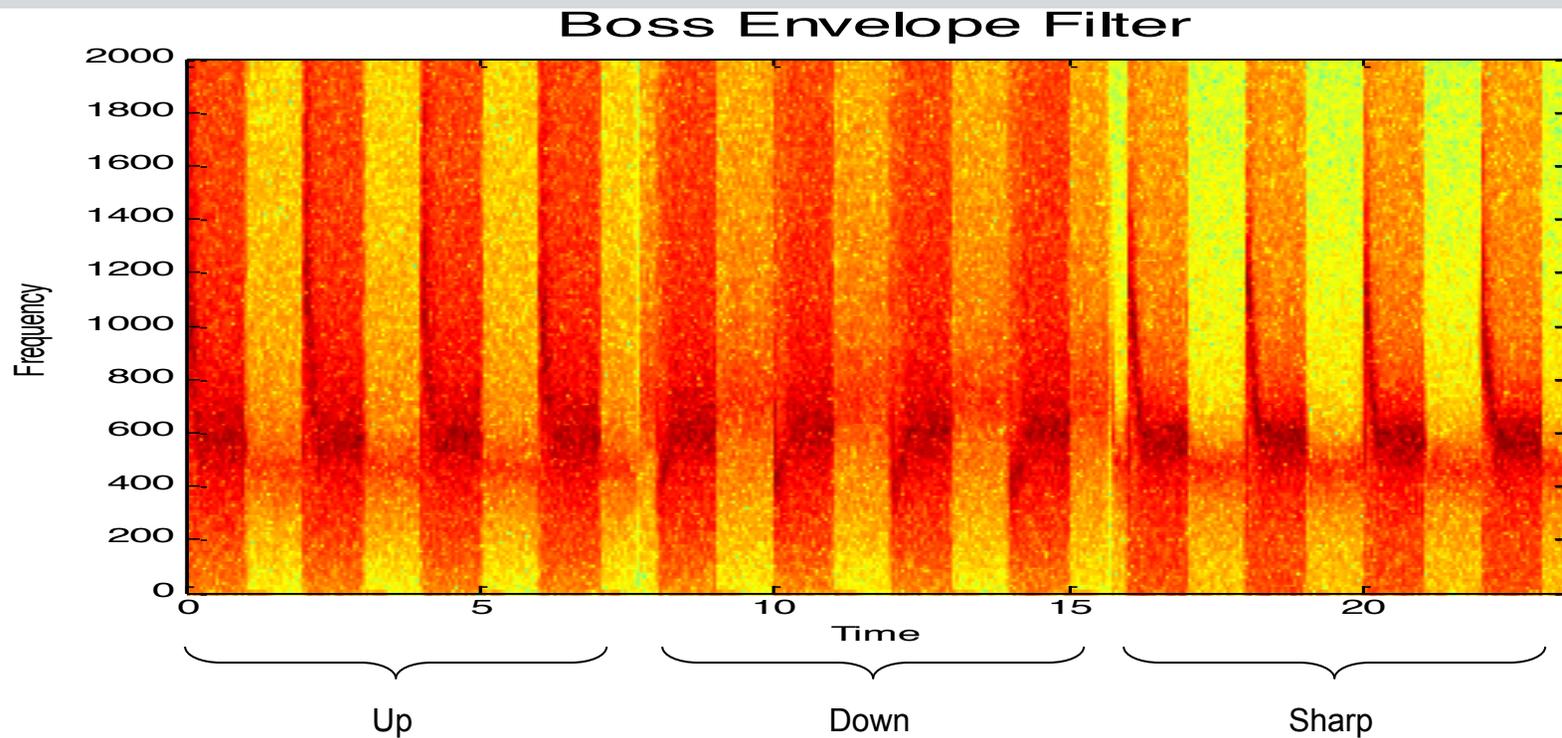
- An envelope filter is a more properly called an envelope controller filter. (It is also possible to control other things with a envelope controller.)
- The most basic envelope filters only sweep from low to high. Others include options for high to low and other variants.
- All envelope filters include a threshold control to determine the amplitude that will make the filter sweep.

Musical Examples:

- What I Am – Eddie Brickell and the New Bohemians
- Higher Ground – Red Hot Chili Peppers



Envelope Filter Responses

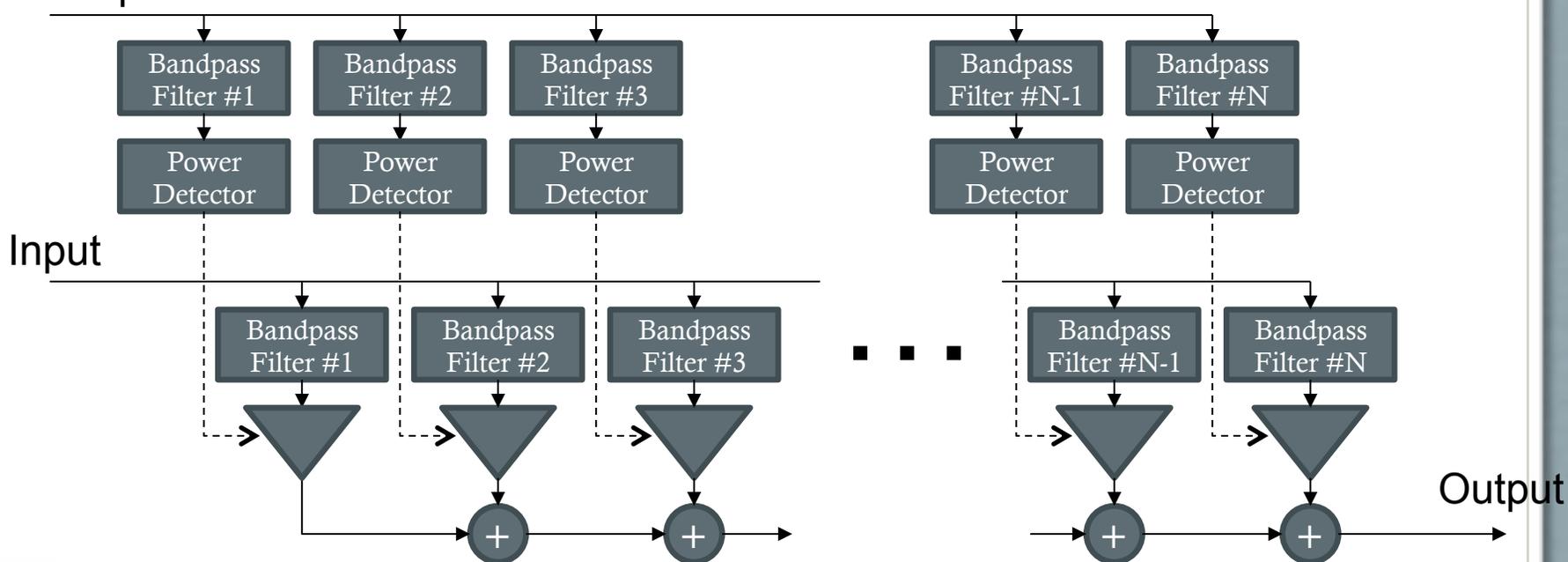


The envelope filter was fed a noise signal with a 20dB amplitude tremolo signal applied to it. The threshold was set such that only the louder sections of the input waveform would exceed the threshold and sweep the wah.

Vocoder

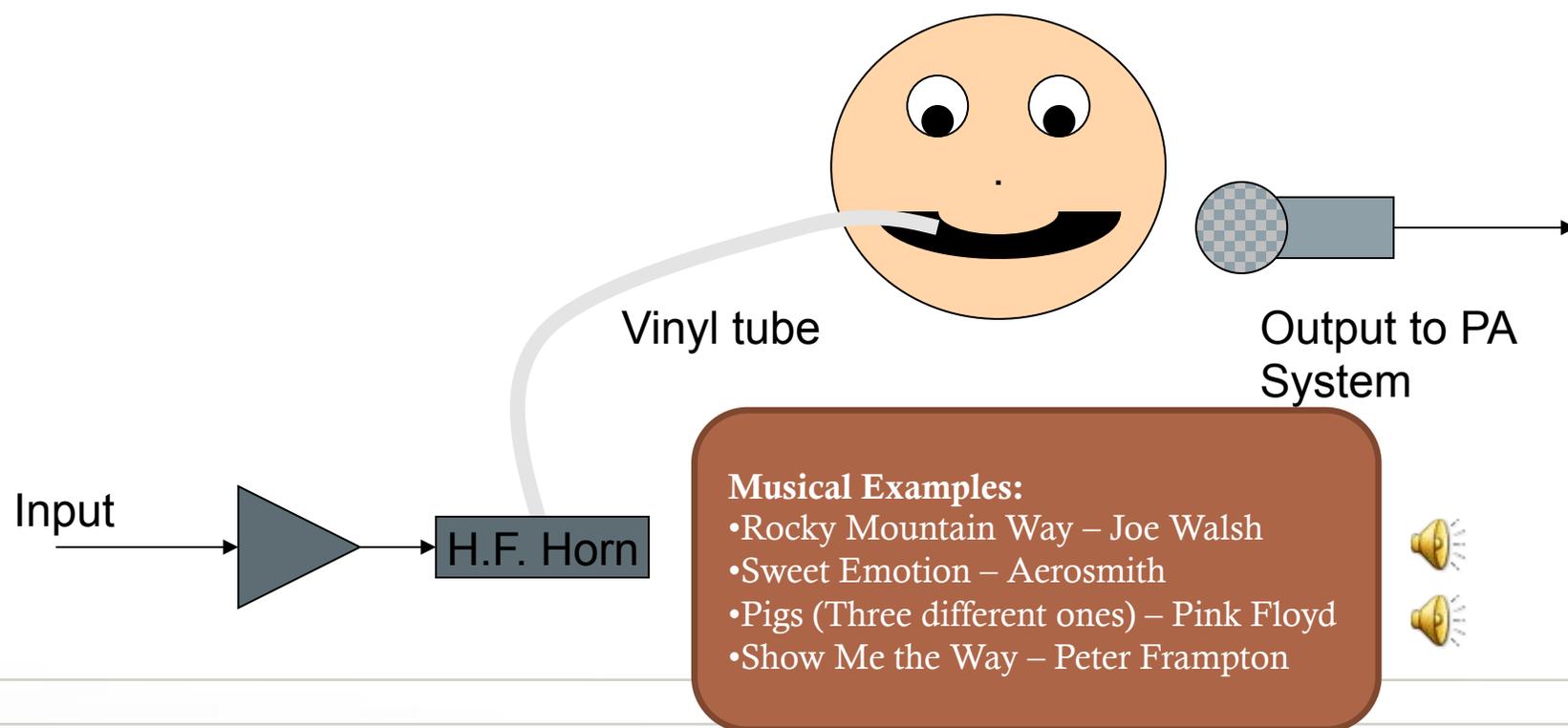
- While the wah creates a human-like sound, it only emulates one particular sound. The vocoder uses a speech input to apply the frequency response of a human voice to the instrument in real time.
- The voice signal is filtered through multiple filters and the power in each band is determined. This power then modifies the gain for a similar band pass structure applied to the instrument input.

Vocal Input



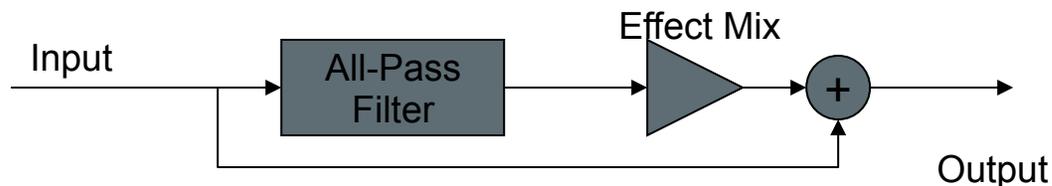
Talk Box

- Often called the “poor-man’s vocoder”. Analog vocoders required many parts and were quite expensive. The cheaper alternative was to route the guitar’s signal throughout the mouth of the guitarist. This proved to also be more popular.



Phase Shifter

- Originally created as a real-time simulation of the flanging effect.
- Typically built as an analog all-pass filter
 - Phase-shift filters have a certain amount of phase shift
 - Multiple stages of phase shift are concatenated to create an even greater amount of shift. This allows lower frequencies to be cancelled.
 - This phase-shift varies with frequency
 - A low frequency oscillator typically modulates the phase-shift stages
- The all-pass filter has variable phase lag which causes some frequencies to pass and others to be "notched"
- The flanger is a special case of the phase shifter
- See handout (http://www.ece.osu.edu/~pavlict/ece209/lab1_intro/lab1_intro_phase_shifter.pdf) for a circuit description of a single stage. Most Phase Shifters include 4 to 12 stages



Musical Examples:

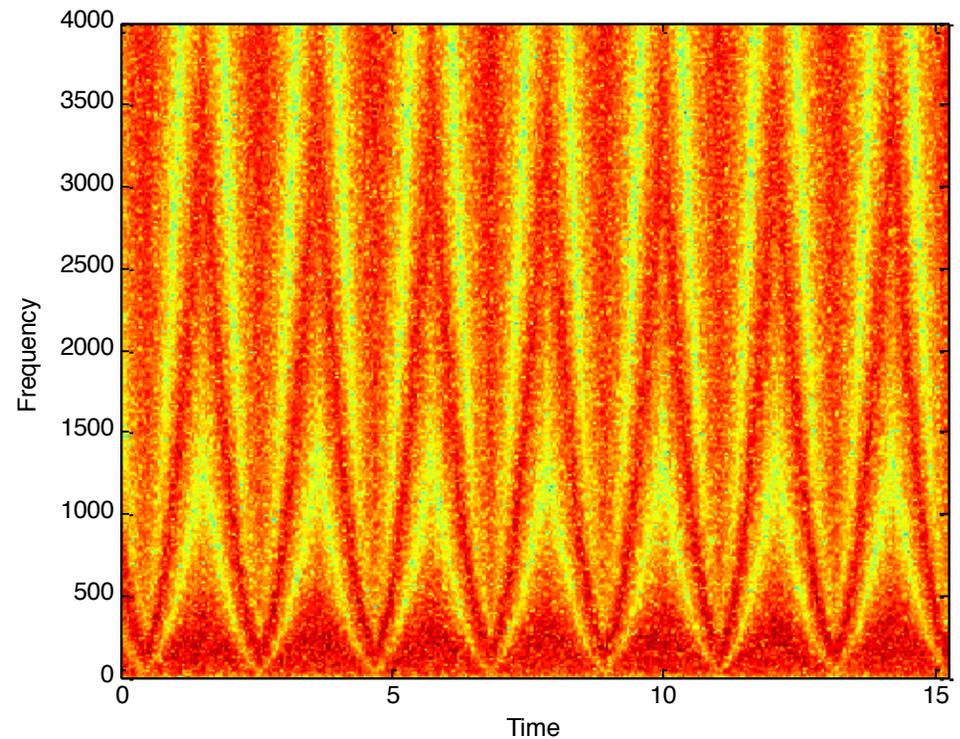
- Ain' t Talkin' 'Bout Love – Van Halen
- No Quarter – Led Zeppelin
- You Belong with Me – Taylor Swift



Phase Shifter Response



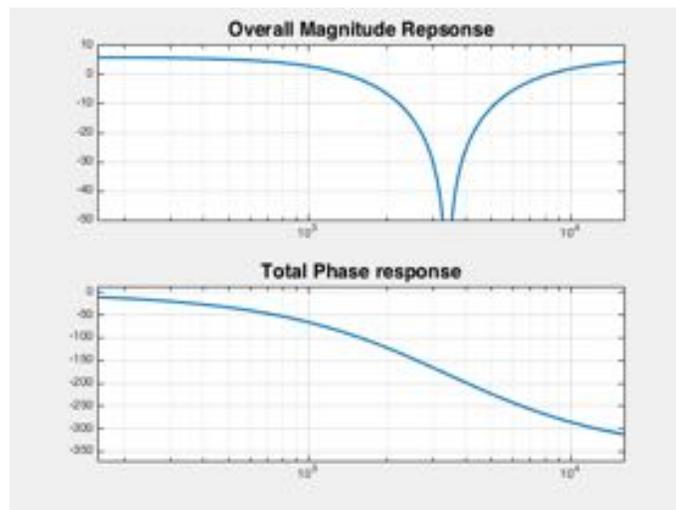
Phase Shifter



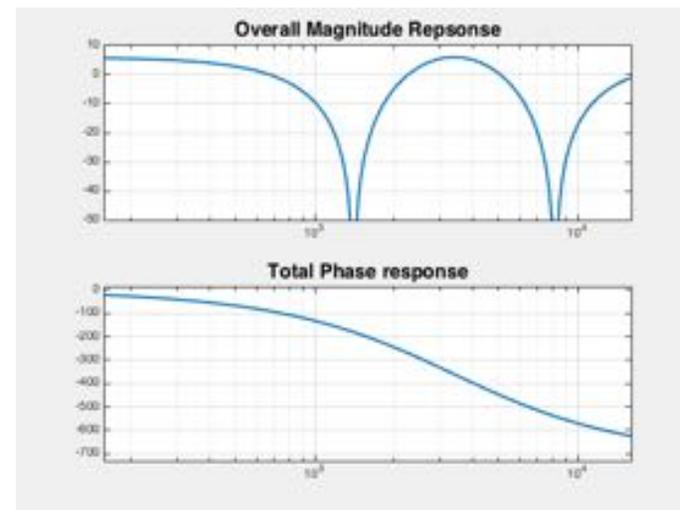
Notice the exponential sweeping of the notches. This spectrogram was created using noise as an input

Matlab Simulation Response

- 2 Stages of phase shift

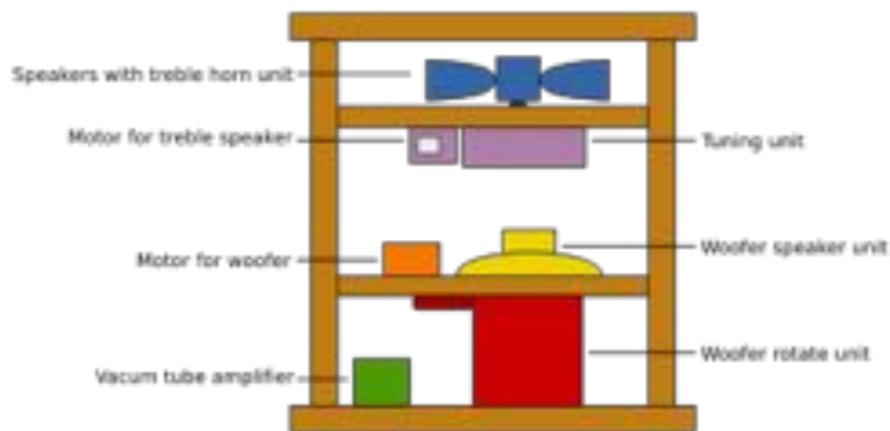


- 4 stages of phase shift



Spinning Speaker

- The Leslie Spinning Speaker is a unique sound that is often copied, but rarely perfectly.
- http://en.wikipedia.org/wiki/Leslie_speaker
- Two Effects in one
 - Tremolo
 - Vibrato (from the Doppler)



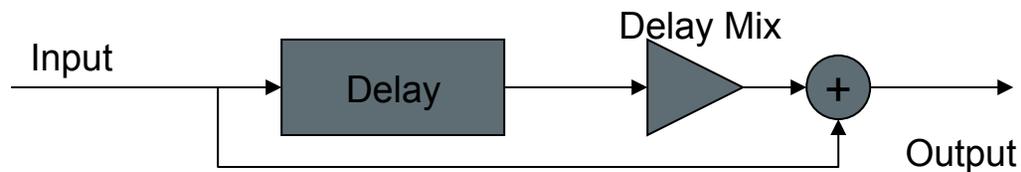
Time Based

- Delay / Echo
 - Digital
 - Analog and Discrete Time
- Reverberation
- Chorus
- Flanging
- Pitch Shifting / Octave Devices

“Analog” vs. Digital

- Many guitarists talk about the difference between “analog” versus digital delay based devices
- In truth, there are no completely analog circuits (except for tape-echo units). In “analog” delay pedals, the delay unit is a bucket-brigade chip
- A bucket-brigade chip is an integrated circuit with a large number of capacitors and transmission gate transistors.
 - The signal is sampled (into discrete time), and the sampled voltage is placed on the first capacitor
 - The sampled voltage is then passed to the next capacitor at the rate determined by the sampling rate control.
 - If the sampling rate is too low, the voltage on the capacitor will “bleed” down and distortion will occur.
 - This gives the signal a “warm” quality that many appreciate.
- Some argue that the companding around the bucket brigade delay adds to the sound. Some modern pedals wrap companding with a digital delay

Delay



- Adds a delayed copy of the input signal to the output signal
- By adjusting the delay to match the tempo, a musical effect can be achieved where it sounds like more notes are being played
- Often delays have a feedback path (like shown on a later slide for the echo effect). Typically however, the maximum gain is less than one
- Short Delays (40-120 mSec) with no feedback are called “slap-back”
- Delay time is usually adjusted by varying the sampling rate. This allows for pitch shifting effects

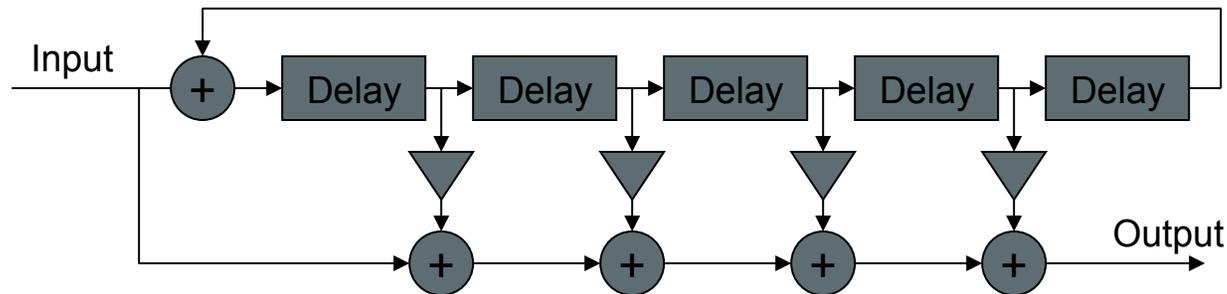


Musical Examples:

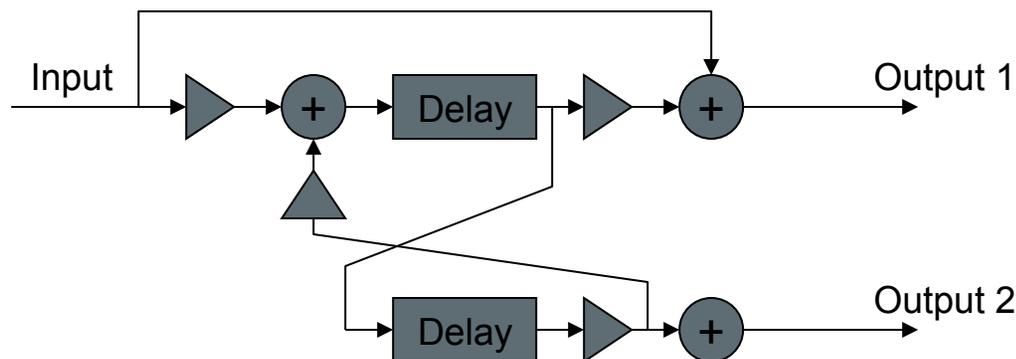
- And I ran – Flock of Seagulls
- Where the Streets have no name – U2
- Run Like Hell – Pink Floyd
- Flight of the Wounded Bumble Bee – Extreme
- Even Better Than the Real Thing – U2



More Delay



- Multi-tap delays include multiple delay elements

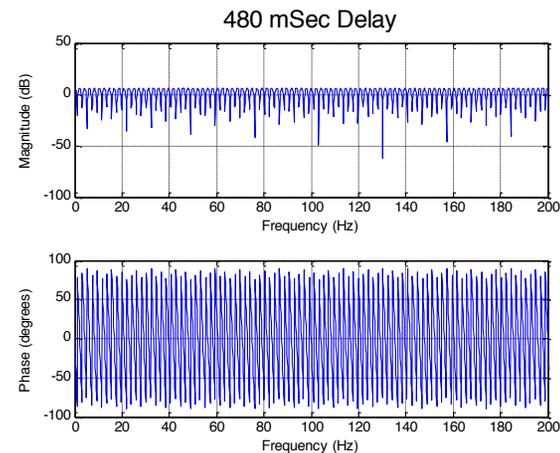
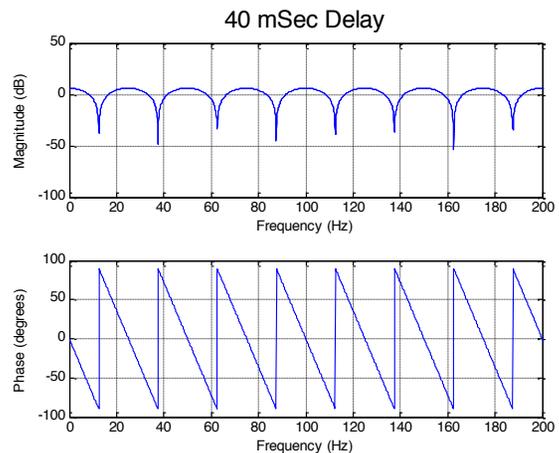


Musical Examples:
• *Most Songs* - U2

- Ping pong delays alternate the signals between the left and right channels

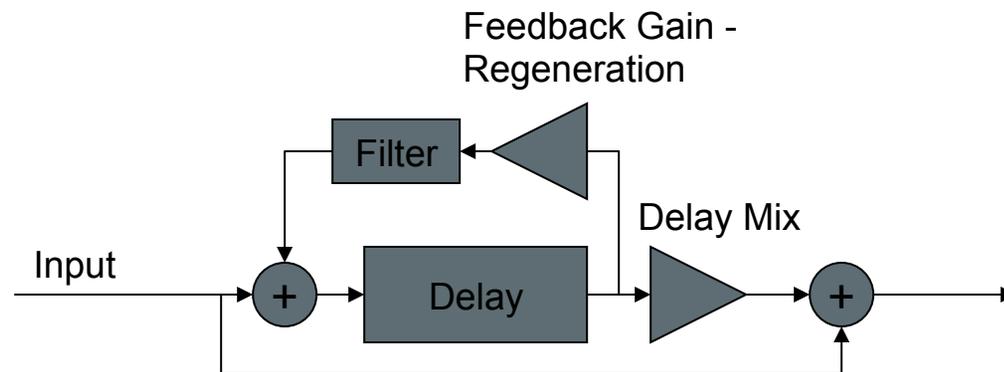
Frequency Response

While it's not usually noticeable, simple delays are frequency selective. It should be obvious that a frequency and all its odd harmonics will destructively interfere and cause nulls in the frequency domain



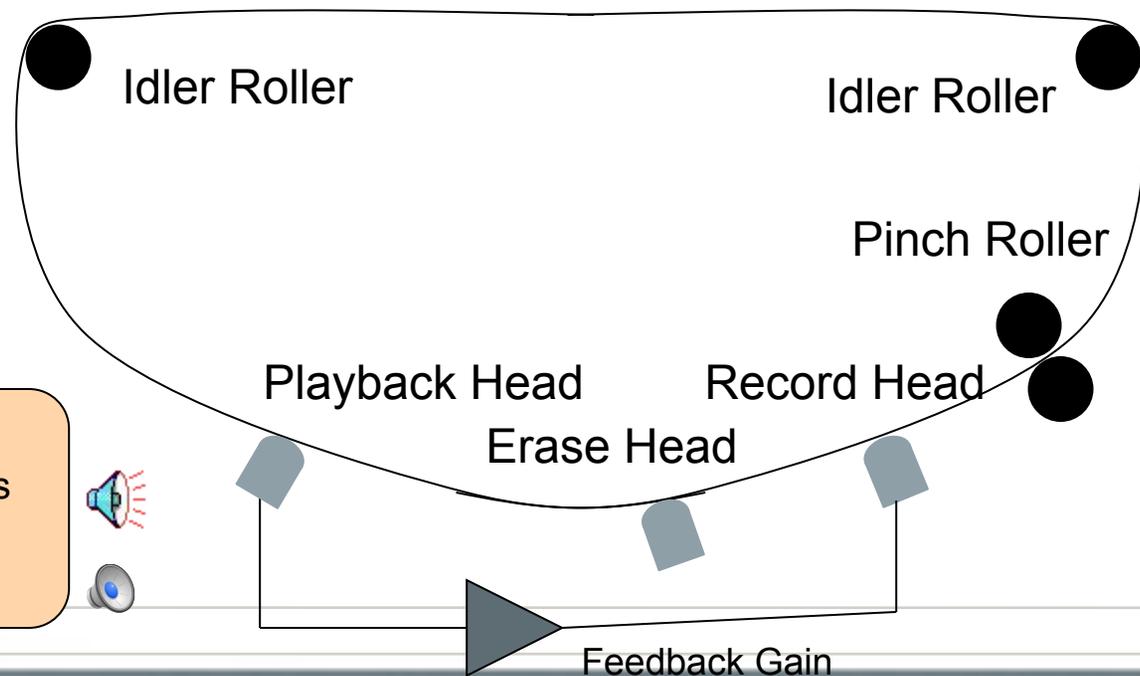
Echo

- Often there is no distinction between delay units and echoes. What usually makes a device more of an echo is how it attempts to simulate a tape echo
 - The feedback gain can be increased to be greater than unity. This will cause the echoes to increase in volume and eventually saturate or oscillate
 - There is sometimes a filter in the feedback loop to simulate the gradual deterioration of signal quality that would occur with a tape-echo unit.
 - Sometimes the delay time is varied slightly to simulate tape warble.



Tape Echo

- Before bucket-brigade or digital, echo units were built using a variable speed tape as the memory storage device.
- Often the playback head was able to be moved to get different delays.
- Changing the tape speed can get crazy pitch shifting effects



Musical Examples:

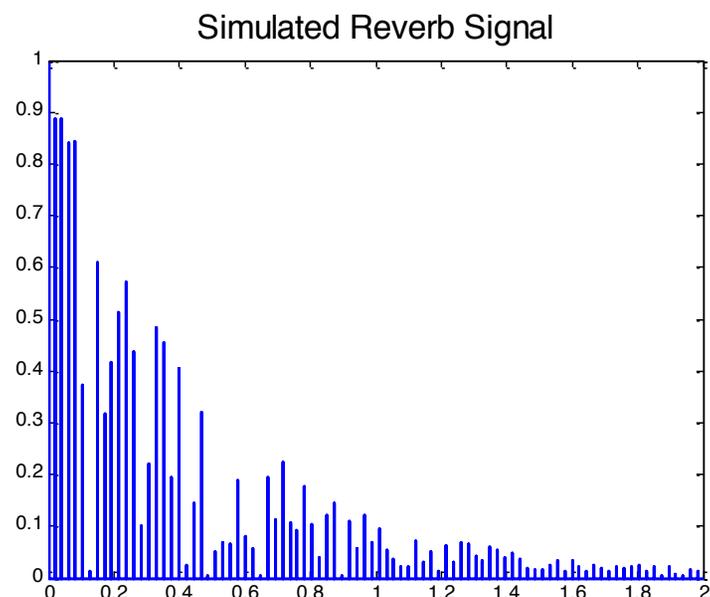
- Standing In the Rain – James Gang
- Quadrant 4 – Billy Cobham

Loopers

- More recent modifications on Delay pedals have allowed musicians to loop indeterminate length sounds.
 - Allows someone to build a bigger and bigger sound
 - Allows one to be their own backing track
- Basic operation isn't very technically difficult
 - Record Button
 - Play Button
 - Erase
- Some Loopers have more advanced controls
 - Revert
 - Reverse
 - Scale

Reverb

- Reverb is designed to sound like the multiple reflections found in a room or a hall.
- Many analog reverbs were created using a spring and transducers
- “True-convolution” is the newest trend in reverbs. This uses an impulse response from a real location. The reverb is effected by using a very long FIR filter
- Can use an FIR filter for early reflections with an IIR filter or the trailing reflections

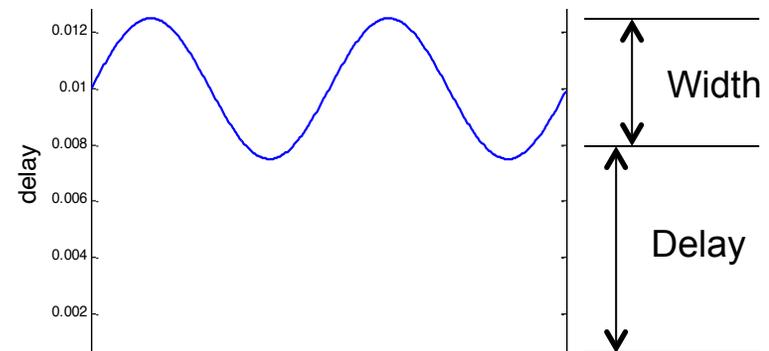
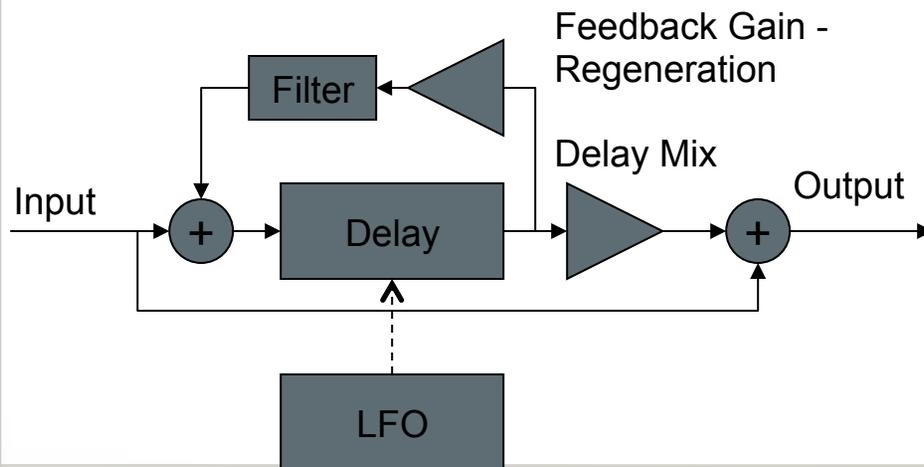


Musical Examples:
• *Domination - Pantera*



Flanger

- As was noticed previously, delay elements can create notches in the frequency domain.
- By changing the delay time continuously (at a sub-sampled value), the notches vary in frequency
- The delay time is modulated with a low frequency oscillator (LFO).
- The following parameters determine the sound from a flanger
 - Delay - The minimum amount of time the signal is delayed. (1 mSec to 10 mSec).
 - Sweep depth (width) - How wide the sweep is in terms of delay time. i.e., the maximum additional delay time added as the LFO is swept (100 ns to 10 ms)
 - Speed – the frequency of the LFO

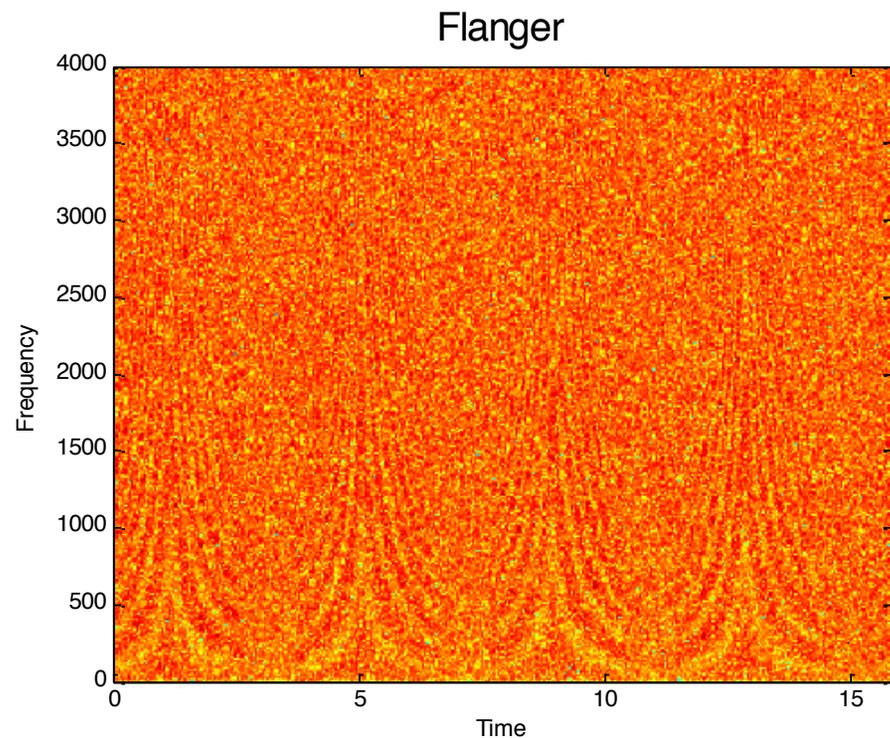


Flanger Response



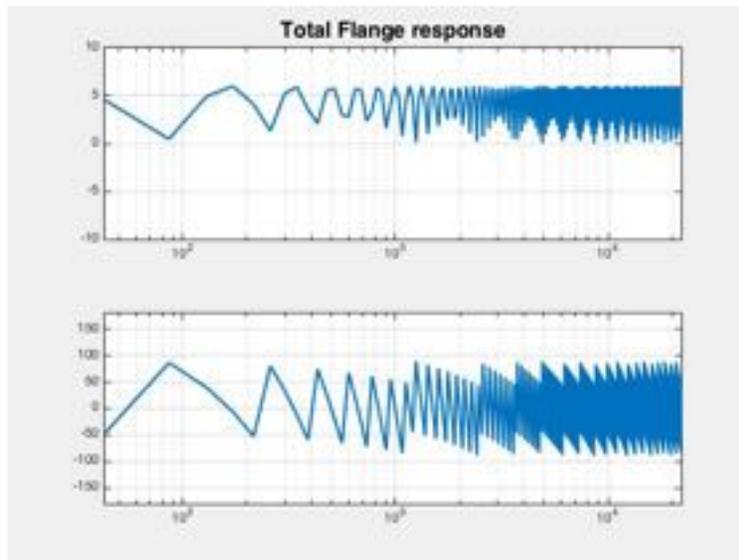
Musical Examples:

- Are You Gonna Go My Way – Lenny Kravitz
- Bold as Love – Jimi Hendrix
- Barracuda - Heart



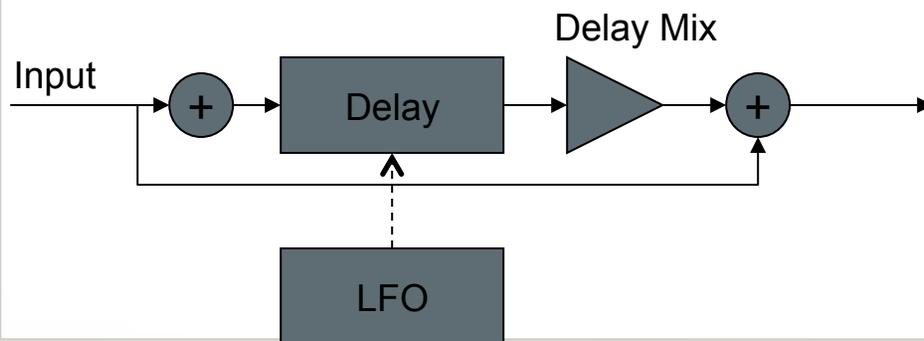
This particular flanger produces a very mild effect. The notches are barely visible. This spectrogram was created using a noise source as the input.

Matlab Simulation Response



Chorus

- Named because it makes one instrument sound like many. Fills up the sonic space in a song
- A chorus is merely a flanger with longer delay times (and usually no feedback)
- The following parameters determine the sound from a flanger
 - Delay - The minimum amount of time the signal is delayed. (20-30 mSec).
 - Sweep depth (width) - How wide the sweep is in terms of delay time. i.e. the maximum additional delay time added as the LFO is swept (0 to 10 ms)
 - Speed – the frequency of the LFO
- Extreme settings will create a vibrato – pitch warble
- Vibrato pedals often include the a mix on the clean signal to remove it from the output



Musical Examples:

- Stranger in a Strange Land – Iron Maiden
- I Don't Know – Ozzy Osbourne
- Run to You – Bryan Adams
- Good Enough – Van Halen
- Come as you are - Nirvana

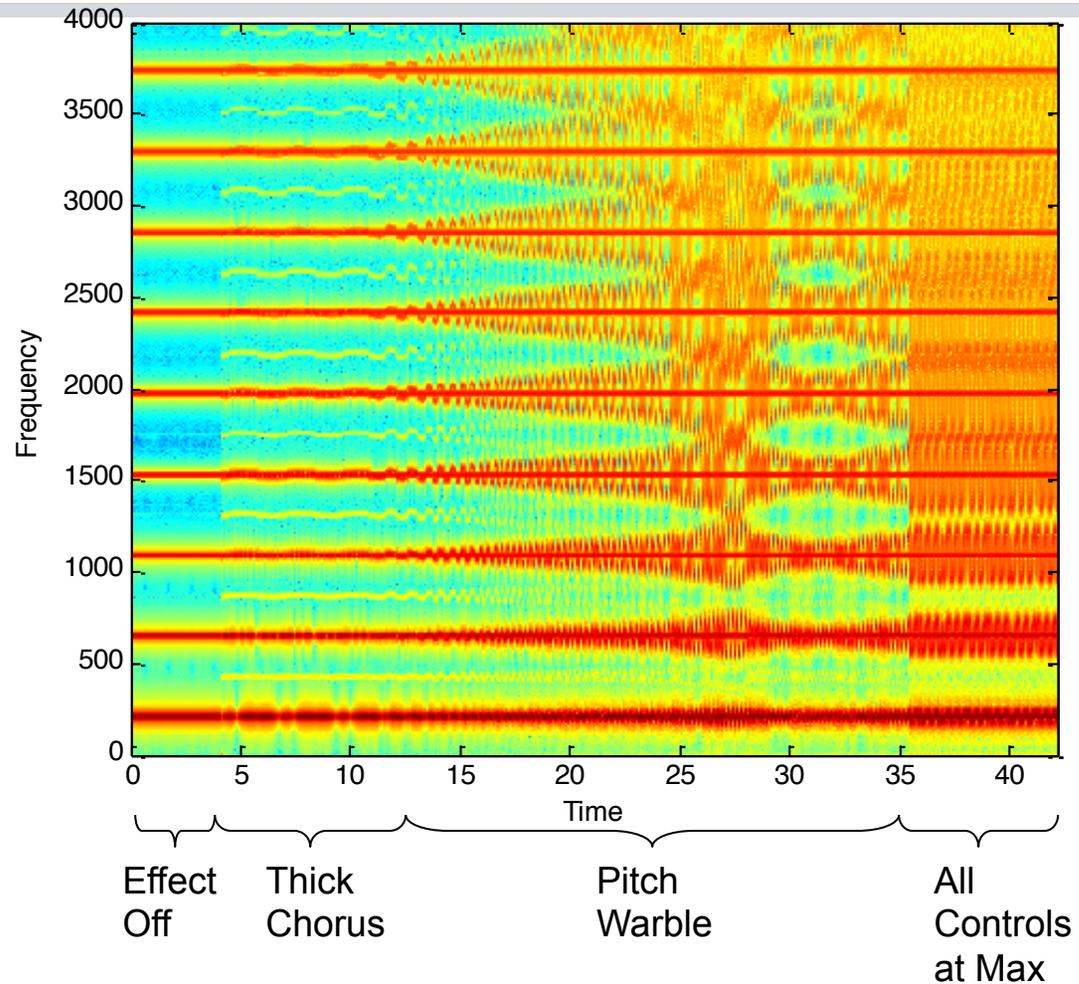


Chorus Responses

Chorus



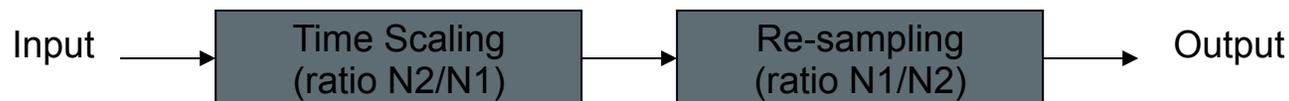
This spectrogram was created using a square wave as the input signal



Modulated Delay

Pitch Shifting

- The 1990s & 2000s addition to effects
- Two types
 - Dumb
 - Simple mathematic ratios determine new note relative to old note
 - Intelligent
 - Key is set (or detected) and harmony is diatonic
- Available as real time in a pedal or post-processing (Auto-Tune)
- Simplest method
 - Time Scaling and Re-sampling
 - PitchScaleSOLA.m from DAFX
 - Phase Vocoder
 - Simulink Example – dsppitchtime.mdl



Multi-Effects

- Combine multiple processing algorithms into a common hardware platform
- Can include analog and digital processing as well as tube and digital processing.
- Use MIDI for patch changes
 - Foot controller for remote control
- Often includes amplifier modeling

References

1. <http://www.harmony-central.com/Effects/effects-explained.html>
2. O' Connor, K., The Ultimate Tone Vol. 1
3. <http://www.geofex.com/fxtech.htm>
4. <http://www.freeinfosociety.com/electronics/schematics/audio/ringmodulator.html>
5. <http://www.microwaves101.com/encyclopedia/mixerwaveforms.cfm>
 1. Explanation of RF mixers which very similar to one implementation of ring modulators
6. http://en.wikipedia.org/wiki/Audio_timescale-pitch_modification
7. http://www.ece.osu.edu/~pavlict/ece209/lab1_intro/lab1_intro_phase_shifter.pdf
 1. Simple Phase Shifter circuit
8. http://en.wikipedia.org/wiki/All-pass_filter

Additional Slides (to be
reworked)

Fuzz Face

